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RADIOISOTOPE

POWER SYSTEMS PROGRAM

Stirling Technical Interchange Meeting

June 29, 2015

Stirling Technical Interchange Meeting

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Agenda

Time	Activity	Presenter	Location
8:00a.m.–8:15a.m.	Registration		Lobby
8:15a.m.–8:30a.m.	Welcome/Introductions/ Safety	John Hamley	President's Room
8:30a.m.–9:00a.m.	Stirling Development	Jim Withrow	" "
9:00a.m.–10:00a.m.	Range of Potential Missions Process	Paul Ostdiek for Ken Hibbard (APL)	" "
10:00a.m.–10:15a.m.	***Break***		
10:15a.m.–11:15a.m.	RFI Overview & Technology Maturation Process	Dawn Pottinger and John Hamley	" "
11:15a.m.–11:45a.m.	GRC Virtual Facility Tour	Lee Mason	" "
11:45a.m.–1:00p.m.	***Lunch***		***On your own***
1:00p.m.–2:00p.m. 1:00pm–1:20p.m. 1:20pm–1:40p.m. 1:40pm–2:00p.m.	Participant Overviews –Sierra Lobo, Inc. –Sunpower, Inc. –TBD		President's Room
2:00p.m.–2:15p.m.	Closing Remarks	John Hamley	" "
2:20p.m.–5:30p.m. 2:20pm–2:40p.m. 2:40pm–3:00p.m. 3:00pm–3:20p.m. 3:20pm–3:40p.m. 3:40pm–4:00p.m. ***4:00pm–4:10p.m.*** 4:10pm–4:30p.m. 4:30pm–4:50p.m. 4:50pm–5:10p.m. 5:10pm–5:30p.m.	One on One Information Dialogues – Infinia Technology Corporation (ITC) – Lockheed Martin Space Systems Co. – Sierra Lobo, Inc. – Sunpower, Inc. – Aerojet Rocketdyne ***Break*** – Teledyne Energy Systems, Inc. – Northrop Grumman Aerospace Systems – Sest, Inc. – TBD		Board Room

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STIRLING DEVELOPMENT

Jim Withrow
Stirling Cycle Technology Development Project Manager

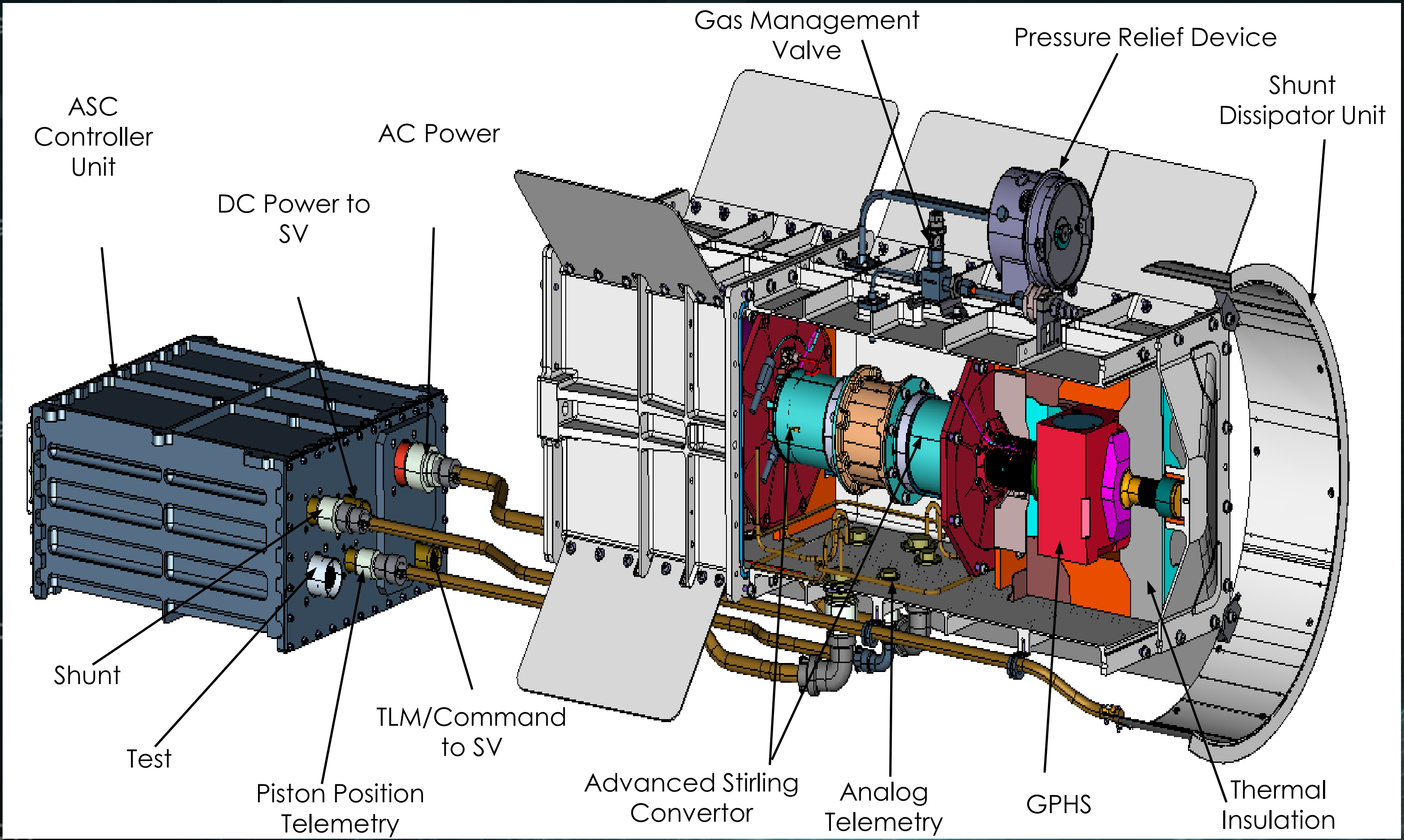
Stirling Technical Interchange Meeting

ASRG HISTORY AT GRC INCLUDING EU2

ASRG Overview

- Stirling Radioisotope Generator program (SRG-110) initiated in 2000 under Department of Energy (DOE) contract to develop high-efficiency thermal-to-electrical power system for future NASA planetary science missions
  - 23% system efficiency vs. 5-7% efficiency for thermoelectric technology
  - Use only 25% of the 238Pu required for a similar power RTG
- Project updated to ASRG in 2006 to use Sunpower free-piston Advanced Stirling Convertors (ASC)
  - 5% higher system efficiency and higher electrical power output vs. SRG110
  - Smaller size and mass vs. SRG110
- Engineering unit ASRG delivered to NASA GRC in August 2008 for extended operations tests (33,000 total hours)
- ASRG original goal to fly on Discovery 12 mission in 2016, but ASRG-powered mission not selected
- ASRG project termination for budgetary reasons in November 2013 while qualification unit ASRG was in fabrication phase

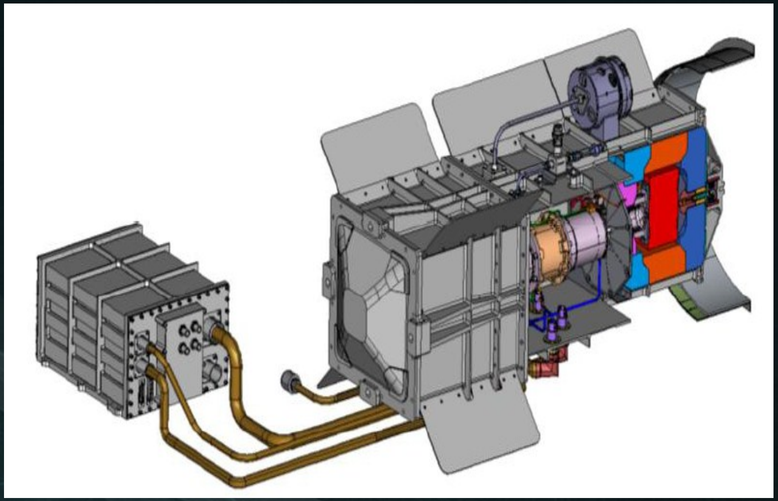
ASRG Flight Configuration



Generator 38 x 38 x 79 cm, Controller 13 x 25 x 30 cm, Total Mass[(1)] = 29 kg

(1) Includes max length ASRG harnesses

ASRG Overview



ASRG EU
Manufactured by Lockheed Martin for the DOE
Provided to NASA GRC in 2008 for Extended Operational Testing

- Advanced Stirling Radioisotope Generator
  - 2 General Purpose Heat Source (GPHS) Modules, each providing 244 W_t minimum heat at the beginning of the mission
  - ASRG Power Requirement – **130 W_e** at the beginning of mission operating in a vacuum environment
  - Predicted Power based on testing – **140 W_e**
  - Mass Requirement – **32 kg**
  - Predicted Mass based on testing – **29 kg**

W_t = Watts Thermal
W_e = Watts Electrical

ASRG Requirements – High Level

- Design & Construction
  - Design, construction in accordance with NASA, DOE, and industry standards
- Performance
  - Power ≥ 130 W_e (BOM); 85% of BOM power output after 14 years
  - Peak transmitted force < 35N
  - Mass ≤ 32 kg
- Environments
  - Ground (storage, transportation, S/C integration, LV integration)
  - Launch (vibration, acoustic, thermal, acceleration – boost & spin)
  - Cruise (planetary fly-by, deep space, radiation)
  - Mission (deep space, planetary – orbit and Mars surface including landing loads)
- Interfaces
  - Electrical power, structural, avionics (control & telemetry), thermal
- Nuclear Safety
  - Include features that protect the nuclear fuel under all scenarios – DOE guidance required
- Reliability
  - Minimum 90% probability of success over mission life (3 year storage, 14 year mission)

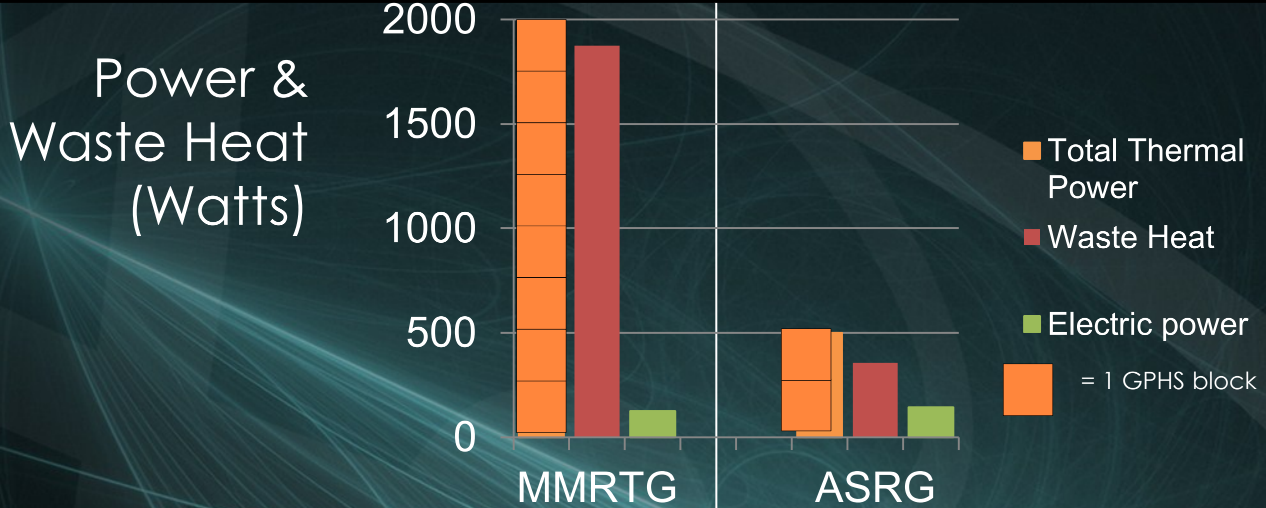
RPS Comparisons from a Mission Perspective

MMRTG

125 W_e Beginning of Mission (BC
68 W_e End of Mission (EOM) (@17 years)
- 57 W_e drop between BOM and EOM

ASRG

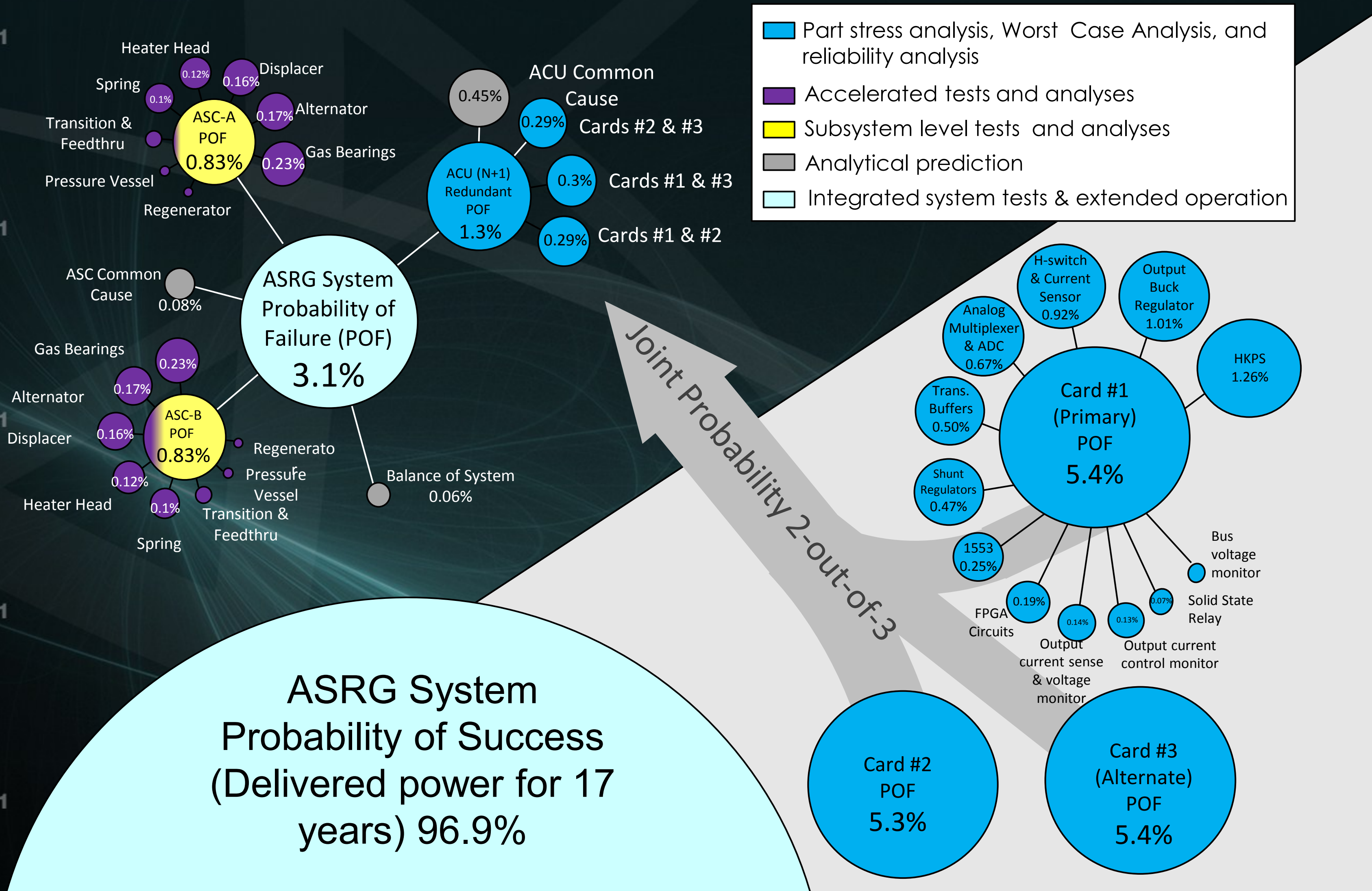
140 W_e BOM
110 W_e EOM (@ 17 years)
- 30 W_e drop between BOM and EOM



Excess heat at 210°C desirable for spacecraft heating (example: Curiosity Mars rover makes excellent use of the excess heat from its MMRTG without the need for additional heat sources like Radioisotope Heater Units (RHU's))

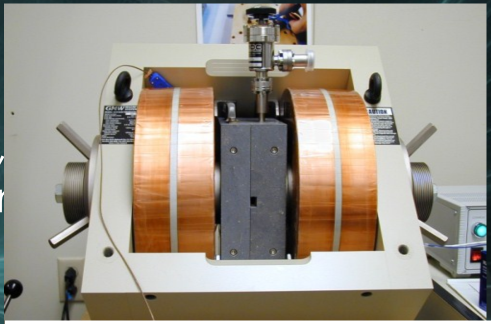
Minimal heat at 80°C desirable for aeroshell integration or spacecraft with instrumentation impacted by the RPS generator's waste heat

ASRG Reliability Prediction



ASRG Reliability Approach

- Some ASRG components had extensive engineering analysis completed to substantiate the design, life, and predicted reliability… however…
- **The ASC design counted on tests to demonstrate reliability of some critical and complex ASC component designs through a rigorous life test program rather than engineering analysis**
  - Multiple ASC's operating in 24 / 7 at GRC in the Stirling Research Lab (SRL) accumulating large numbers of failure free operational hours
    - Periodic shutdowns to accommodate instrumentation calibration, heater replacements, and other support infrastructure maintenance
  - Some components within the ASC had specific life test hardware developed with many tests executed
    - Accelerated spring testing, Organics testing of Loctite, Electrical feed through testing, testing (magnet gauss strength at maximum qualification levels), Etc.


GRCs Magnet Aging Apparatus

ASC-E3 Testing in Support of ASRG Reliability

Delivery Date	Total Hours	Serial	Sequence						
11/30/12	4,287	ASC-E3 #1	2,353	807	1,179	stopped			
11/30/12	4,282	ASC-E3 #2	2,348	807	1,179	stopped			
11/15/13	11,129	ASC-E3 #3	5,113	943	2,000	3,073	ongoing		
08/21/13	11,979	ASC-E3 #4	3,909	17	2,000	1,732	943	3,378	ongoing
08/22/14	5,564	ASC-E3 #5	3,272	865	867	560	ongoing		
08/22/14	5,567	ASC-E3 #6	3,275	865	867	560	ongoing		
02/20/15	947	ASC-E3 #8	947	ongoing					

All hours reported as of 6/14/15

^ Out of sequence, this plan developed after E3 #4 had accumulated hours in other test phases

Reference: Lewandowski, E.J., Bolotin, G.S., and Oriti, S.M., "Test Program for Stirling Radioisotope Generator Hardware at NASA Glenn Research Center," in proceedings of *12th International Energy Conversion Engineering Conference (IECEC-2014)*, AIAA 2014-3964.

Test Seq.	1	2	3	4	5	6
Description	Hardware Acceptance Review, Approval, Transportation to GRC	Characterization, Independent Performance Verification	Simulated Integration & Storage (horizontal)	Simulated Dynamic Environment, including Flight Accept. & Launch Sim.	Early-Life Phase (Looking for "Infant Mortality" failure)	Simulated Cruise
Configuration, Orientation	Delivered in Common Performance Hardware (CPH), single vertical	CPH, single vertical	CPH, single or dual-opposed horizontal	Single horizontal	Single or dual-opposed vertical	Single or dual-opposed vertical
Duration	No limit on production hours, delivered with 400 to 1,000 hrs	No limit, ~2,000 hrs	Specified, 800-1,000 hrs,	No limit, ~10 hrs,	TBD (possible ~2000 hrs)	TBD (possible ~10K hrs)

Reliability Growth: Testing Approach for ASRG

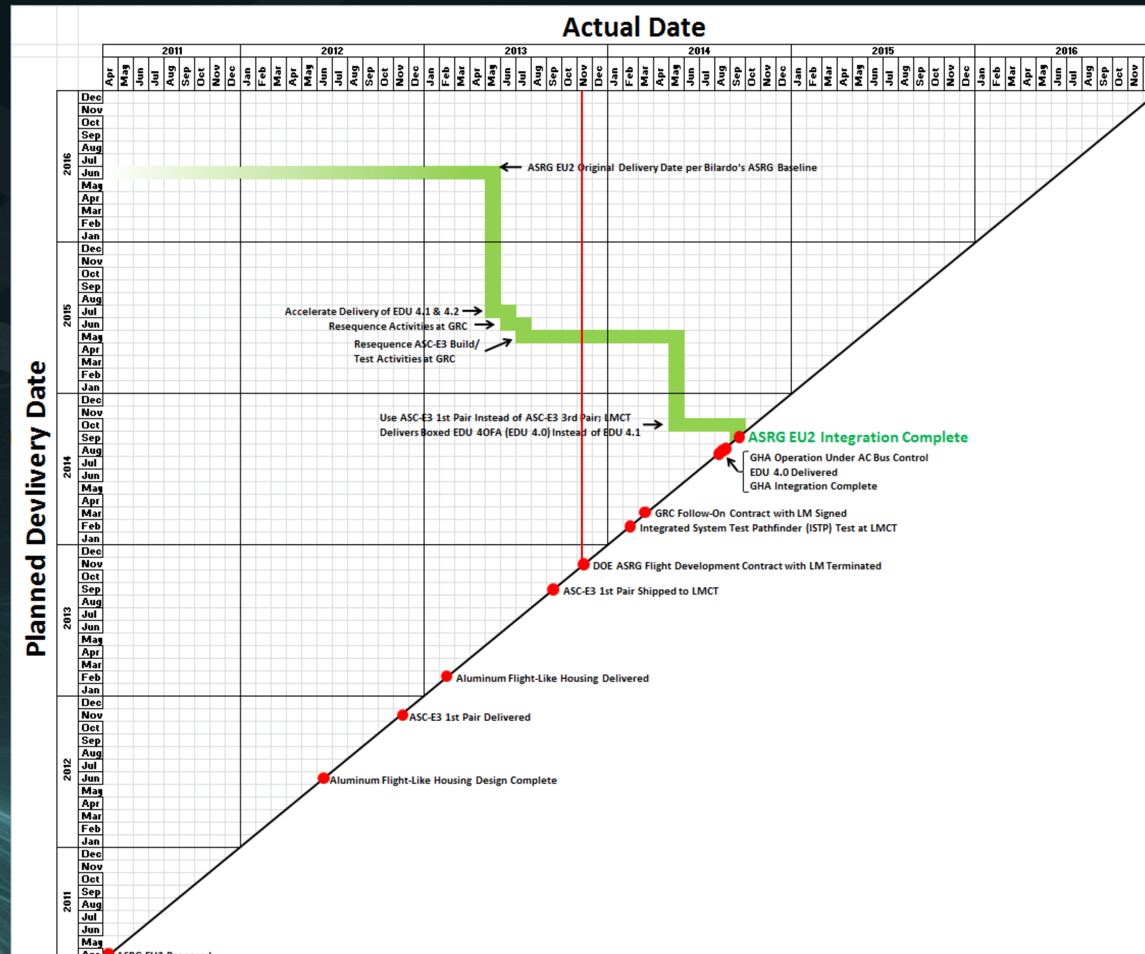
The reliability growth testing approach is sometimes referred to as Test-Analyze-Fix-Test (TAFT)

What was missing?

- Nuclear Power Assessment Study (NPAS) Workshop held in November 2014, showed that the mission centers (JPL, APL, and GSFC) that would integrate ASRG's, believed that the ASRG reliability approach needed:
  - **Physics based models, validated through goal-based testing**
- The mission centers all agreed that although the probabilistic approach that relied on testing had been planned for ASRG was approved at CDR, they were uncomfortable with the qualitative and empirical testing and highly desired a quantitative approach to reliability

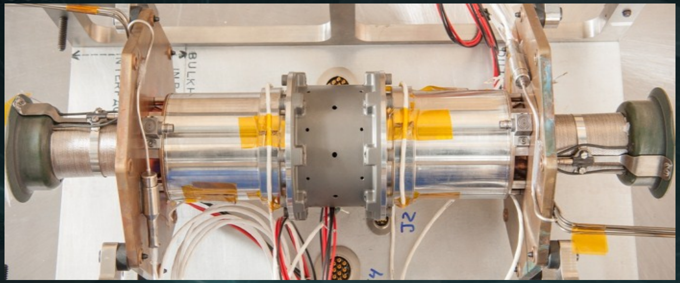
EU2 Planning

- EU2 Originally planned to be completed in June '16 at GRC based on hardware availability
- EDU 4 acceleration on the DOE contract, along with use of different ASC's allowed EU2's completion at GRC, 21 months early



Components of the ASRG EU2

Integrated power system:

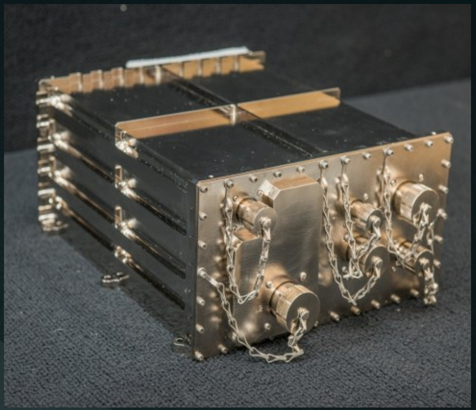


Sunpower ASC-E3 #1 and #2

+

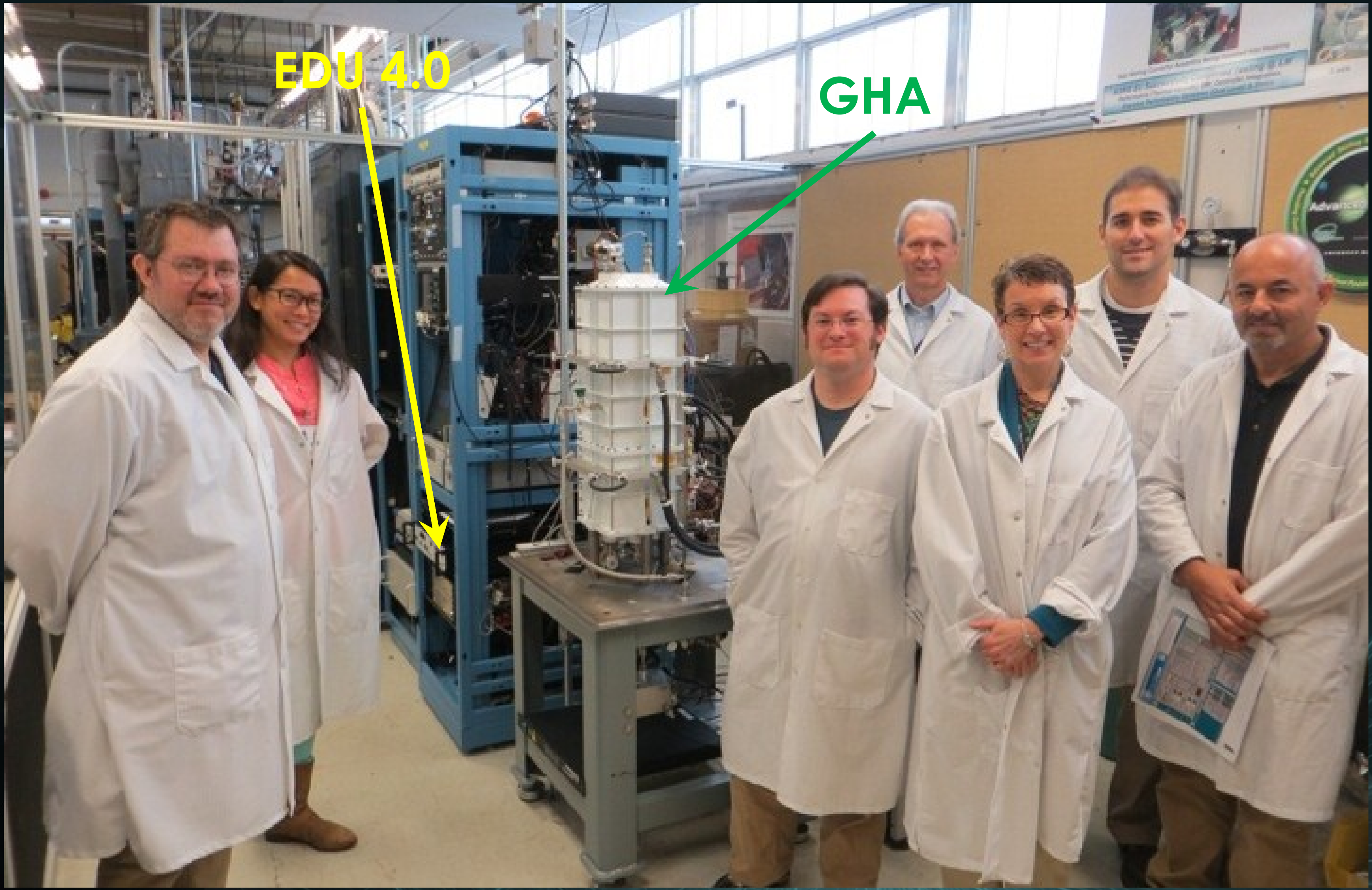
GRC aluminum flight-like housing

+



Lockheed Martin EDU 4 Controller

ASRG-EU2



EU2 First Operation: September 19, 2014

Future SRG Approach

- Although the ASRG requirements have been developed with hardware tested, and with the help of EU2, we can show ASRG operational performance can meet the requirements…
  we are revisiting the requirements for the next SRG and are looking to move from ultra-low mass and ultra-high efficiency to a robust approach
- Robustness and reliability prioritized over mass and efficiency

The References Below Provide General Information on Various Aspects of the ASRG Project

- Project Kickoff as SRG-110
  - Schreiber, J.G., and Thieme, L.G., "Final Results for the GRC Supporting Technology Development Project for the 110-Watt Stirling Radioisotope Generator (SRG110)," in the proceedings of Space Technology and Applications International Forum (STAIF–2007), edited by M.S. El-Genk, AIP Conference Proceedings, Melville, NY, 2007
- ASRG-EU Testing at LMVF
  - Chan, J., Hill, D., Hoye, T, and Leland, D., "Development of Advanced Stirling Radioisotope Generator for Planetary Surface and Deep Space Missions," Proceedings of the Sixth International Energy Conversion Engineering Conference (IECEC 2008) American Institute for Aeronautics and Astronautics, 2008.
  - Chan, J., Wood, J.G., and Schreiber, J.G., "Development of Advanced Stirling Radioisotope Generator for Space Exploration," proceedings of Space Technology and Applications International Forum (STAIF 2007), edited by M.S. El-Genk, AIP Conference Proceedings 880, pp. 615-623, 2007; NASA/TM—2007-214806.
- ASRG EU Testing at GRC
  - Lewandowski, E.J. and Schreiber, J.G., "Testing to Characterize the Advanced Stirling Radioisotope Generator Engineering Unit," Proceedings of the Eighth International Energy Conversion Engineering Conference (IECEC 2010), American Institute for Aeronautics and Astronautics, 2010.
  - Lewandowski, E.J., et al., "Design of a Facility to Test the Advanced Stirling Radioisotope Generator Engineering Unit," Proceedings of the Seventh International Energy Conversion Engineering Conference (IECEC 2009) American Institute for Aeronautics and Astronautics, 2009.
- ISTP testing of ACU at LMCT
  - Chan, T., Wiser, J., Brown, G., Florin, D., and Oriti, S.M., "System-Level Testing of the Advanced Stirling Radioisotope Generator Engineering Hardware," Proceedings of the Twelfth International Energy Conversion Engineering Conference (IECEC 2014) AIAA, Cleveland, OH, 2014.
- GRC completion of EU2
  - Oriti, S.M., "Advanced Stirling Radioisotope Generator Engineering Unit 2 (ASRG EU2) Final Assembly," Proceedings of the Nuclear and Emerging Technologies for Space 2015, Albuquerque, N.M., February 23-26, 2015
- GRC initial testing of EU2
  - Forthcoming IECEC paper: Lewandowski, E.J. and Oriti, S.M., "Characterization of the Advanced Stirling Radioisotope Generator EU2, " IECEC 2015, Orlando, FL July 27-29, 2015.
- Other good references:
  - Schreiber, J.G., "Developmental Considerations on the Free-Piston Stirling Power Convertor for Use in Space," in the proceedings of 4th International Energy Conversion Engineering Conference, American Institute of Aeronautics and Astronautics, Reston, VA, 2006, AIAA–2006–4015.

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Range of Potential Missions Process

Kenneth Hibbard
Stirling Radioisotope Generator Integration Manager

Need for Stirling Radioisotope Generators

- Leverage work from recent Nuclear Power Assessment Study (NPAS) released in April 2015
  - NPAS team included broad list of participants
    - NASA (RPS Program Office, SMD, STMD, HEOMD, NASA Nuclear Flight Safety Assurance, JSC, KSC, GRC)
    - Department of Energy
    - Major robotic mission centers (APL, GSFC, JPL)
    - National Laboratories (INL, SNL)
    - Independent engineering and safety consultant (e.g. Sholtis)
  - NASA's need for RPS to enable robotic scientific missions for planetary exploration has been a "given" for over 4 decades
  - There are well-known benefits of more efficient power systems, including the ever-present need to minimize mass, as well as efficient use and stewardship of the limited supply of Pu-238

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Relevant NPAS Broad Conclusions

- NASA will need appropriately sized nuclear power systems to support robotic space missions for the period covered by the decadal surveys currently in force
  - The 2011 Planetary Decadal Survey makes it clear that nuclear power systems are enabling for the implementation of high-priority planetary science missions
  - No known chemical, solar, or other nonnuclear power supplies that fulfill the need
- This need for nuclear power systems is expected to extend for at least one more decade past that covered by the current decadal surveys.
  - Given (1) current budget levels, (2) decadal survey priorities, and (3) NASA requirements as expressed to the DOE (most recently in 2010), nuclear power systems are expected to be required well into the 2030s at the least
- RPS with projected Pu-238 production rates and current technology may suffice to fulfill currently projected SMD needs
- Significantly increased capability in the rate of RPS electrical power available for missions is possible only with increased Pu-238 production rates and/or flight qualification of a dynamic converter

Potential Stirling RPS Missions (documented)

- The continuing need for planetary missions has been articulated clearly during the last decade from the NRC report of 2009 through the Planetary Decadal Survey of 2011, "Vision and Voyages"
  - Lunar Geophysical Network
  - Europa (although, recently baselined solar power)
  - Titan Saturn System Mission
  - Saturn Probe
  - Uranus Orbiter and Probe
  - Trojan Tour
  - Enceladus Orbiter
  - Io Orbiter

- RPS, specifically Stirling systems, had been identified as enabling for nine potential Discovery missions, funded for closer study under the Discovery and Scout Mission Capabilities Expansion (DSMCE) investigation in 2007
  - The last Discovery Step-2 selections included two ASRG-enabled concepts
    - Titan Mare Explorer (TiME)
    - Comet Hopper (Chopper)
  - The only non-nuclear Step-2 concept, InSight, was ultimately chosen

Stirling to Flight (S2F) Initiative

- Objective:
  - Develop a 100-500 W_e Stirling generator system for integration onto a mission launch opportunity NET 2028 that is robust, manufacturable, reliable (fault tolerant, long-life) with reasonable life-cycle and sustainability costs.
- Approach:
  - Tailor the e-MMRTG Technology Maturation operational and evaluation model
  - Form Cross-Organizational Team
    - Radioisotope Power Systems Program (NASA)
    - Department of Energy (DOE)
    - Technology and Mission Centers (GRC, APL, GSFC, JPL)
  - Two efforts integrate to make the S2F project which culminates in the DOE Flight System development
    - A Stirling System Technology Maturation Effort
    - A Surrogate Mission Effort to provide clear mission pull and requirements context

S2F SMT Charter

- S2F Surrogate Mission Team (SMT)
  - Organize Stirling Integration in similar manner as RTG processes
  - Create a Surrogate Mission Team that functions as the mission during the Stirling generator system development until an actual first flight mission is identified
  - Ensures mission requirements, perspective, trades are completely integrated throughout the S2F technology & maturation development S2F project
  - SMT represents the "mission" pull and perspective for the S2F project
    - Treats S2F as a "flight" development rather than a pure technology endeavor
    - SMT serves as the technical authority for the S2F requirements
  - Delivered Products
    - SEMP
    - Mission Need Statement
    - DRM(s)
    - Preliminary Concept of Operations
    - Risk Informed Lifetime Testing
    - S2F Requirements
    - Risk Management

SMT to Define Needs and Requirements for S2F System

- Needs
  - These will largely be based on the existing information from NPAS and other past studies, as summarized earlier
  - Will work with DOE to develop required Mission Needs Statement
- Requirements
  - A systematic, or systems engineering, process will be utilized
  - The Stirling power system will be placed in proper context
    - Required to be a stand-alone delivery
    - Will be considered within the full life-cycle context of a NASA mission, meaning that development, integration and test, and operational considerations will all be accounted for
    - Will be viewed as part of a larger spacecraft [power] system, and therefore may not need to perform as an isolated, independent system (lesson learned from ASRG)
  - Requirements will be defined at appropriate levels (mission, spacecraft, subsystem, unit, component, etc.), as is common for all NASA missions
  - Requirements development and verification will be an iterative process consistent with the NASA's documented processes

Design Reference Mission

- One of the early steps is to define an appropriate Design Reference Mission (DRM)
  - This will not be a specific mission to a specific destination
  - Rather, it will represent a generic mission that could support a variety of desired, potential exploration targets
- Intended to be inclusive, not exclusive
- Will try to address concerns and needs specific to SRG
  - For example, while desired power levels for could be met by the MMRTG / e-MMRTG or SRG, the implementations are not always interchangeable due to the additional waste heat generated by the TE (compared to Stirling converters)
  - Want to acknowledge that S2F will be the first flight of a new technology, and as such the initial system should avoid setting the bar too high and seek a reasonable (TBD) first implementation
    - E.g., avoid excessive requirements for efficiency, lifetime, other
    - Incorporate lessons learned from previous efforts (i.e., ASRG)

DRM Initial Requirements Definition

- Initial step will be for the SMT to assess existing mission concepts requiring RPS, and pull out the driving requirements
  - Include power system requirements (functional, physical, and performance), environment requirements (both pre- and post-launch), launch requirements, safety requirements, I&T and handling requirements, operational requirements, reliability, NEPA, etc.
  - Since the SMT includes representatives from NASA, DOE, and each of the major mission centers, specific staff will be asked to research the concepts and studies performed at their respective institutions and bring forward the relevant information in a manner that can be utilized by the team
    - Ensures investigation at the necessary level of detail to be successful
    - Protects the IP of individual concepts and organizations
    - E.g., GRC civil servant will be asked to examine the DSMCE studies
- Once this set of mission requirements has been created, the SMT will review for over-lap, identifying those requirements common across SRG-enabled concepts
- Next the "outliers" will be assessed for consideration to ensure the SRG DRM is as inclusive as possible
- Final mission requirement set will be documented and forms the basis of the S2F DRM

Continued S2F DRM and Requirements Development

- The DRM requirements will be allocated from the mission to the appropriate level
  - Systems (e.g., NEPA), safety and mission assurance, spacecraft, operations, obs. I&T, etc. – NASA WBS Level-2
  - Subsystems (power, thermal, avionics, etc.) – Level 3
  - Units (Stirling generator, controller, etc.) – Level 4
- A preliminary concept of operations will be developed for the S2F system, accounting for all phases of the life-cycle, including flight operations
- A key component of the S2F effort is risk-informed lifetime testing
  - Phase 1 – Plan (establish Risk-Informed Life Test program plan, define EOL success criteria for the system, define framework for top-level reliability model of system), and Data Assessment and Data Collection (evaluate previous ASRG test results for use in life model and support RFI process)
  - Phase 2 – Model Development (evaluate Lifetime requirements and con ops, develop complete physics-based reliability model)
  - Phase 3 – Testing (incorporate test results in the POF Reliability Model, periodically update POF Reliability Mode with new, if any, failure modes)
- Risk management will be performed through the S2F development to ensure risks are captured, evaluated, and factored into the design process from a mission success perspective

Typical Concerns with RPS Systems

- From a mission implementation perspective, there are a variety of common concerns that need to be addressed when using RPS. Some of these are below (not an all inclusive list)…
  - Minimizing mass is always a concern and principal objective for space missions.
  - As the primary power source for the mission, the power output must be able to be reliably predicted throughout the mission lifetime
  - Nuclear power systems tend to produce radiation emissions; many of the target destinations may involve radiation challenges, so minimizing any "self-induced" radiation complications from the RPS is desired.
  - Mechanically, spacecraft and science instruments do not like any extraneous vibrations or jitter, so RPS should look to minimize any induced vibrations fed into the larger flight system
  - There is value to having flexibility in how RPS are integrated into the spacecraft (cantilevered, vertical/horizontal mounting, within capsule, etc.), as well as being able to treat RPS as modular elements so that multiples can optionally be used on a single mission.
  - Typically, RPS flight units are integrated onto the spacecraft late during the final launch site processing once the spacecraft has already been encapsulated into the launch vehicle fairing.
  - In the past, SRGs need to be under constant control once they are fueled and active. This creates challenges for integrating both generators and controllers into the spacecraft, for interfacing between GSE and flight units, and in-flight during potential anomalies and interactions with the larger spacecraft power architecture.
  - Thermal environments and mitigations tend to become mission drivers, as the RPS performance often depends on the thermal operating environment. Therefore, being able to thermally accommodate RPS without imposing significant power or other controls from the flight system is helpful. Equally beneficial is for the RPS to preform in a broad range of thermal environments. Flexibility in techniques for utilizing waste heat is also highly beneficial.
  - Waste heat from RPS can impact a mission's ability to make key science measurements, especially common temperature measurements, without imposing complicated means of accessing the target environment away from the RPS location.

Typical Concerns with RPS Systems (continued)

- From a mission implementation perspective, there are a variety of common concerns that need to be addressed when using RPS. Some of these (not an inclusive list) are below…
  - Like all flight elements, operations will desire telemetry insight into key performance parameters and access to commands to manage any "control knobs" available.
  - Fault protection and fault management need to be able to interact with SRGs and controllers to provide a total flight system tolerant to potential faults and failures.
  - Stirling power systems need to interface with other power and avionics elements, requiring (ideally) simple, well-defined interfaces consistent with existing technologies (e.g., SpaceWire/RS422 data interfaces, common power connections, batteries and/or capacitor banks, shunts, etc.)
  - Stirling systems will need to perform in prelaunch (Earth atmosphere, 1-g, etc.) environment; launch conditions (vibe, thermal, acceleration, etc.) presently on Atlas, Falcon, and/or SLS launch vehicles; and both deep-space (vacuum, qualification temp. range from -40° C to +60° C) and target destination environments (various temperatures, radiation levels, dust/particles, gravity levels, pressures, etc.)
  - Stirling systems will need to reliably survive for > 10 (TBD) years, necessitating need to assess performance and produce risk-informed lifetime models (from system down to individual components) to evaluate reliability
  - Typical spacecraft and planetary missions must address EMC/EMI requirements, largely driven by payload needs (especially for those missions with magnetic or fields science measurements).
  - Typical missions will require relevant simulators, models, and test units (analytical thermal model, analytical structural model, analytical behavioral model, radiation model, mass model, electrical model, thermal model, fit-up model, flight model, EMI/EMC test unit, GSE, test equipment, pathfinder unit, etc.)
  - There will be a variety of safety and handling requirements that must be addressed to meet NEPA and Launch Approval Engineering requirements, and DOE processes and standards.

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BREAK

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RFI Overview And Technology Maturation Process

Dawn R. Pottinger
NASA Glenn Research Center Contracting Officer

John A. Hamley
RPS Program Manager

Stirling Technical Interchange Meeting

RFI NNC15MR015L OVERVIEW

Dawn R. Pottinger
NASA Glenn Research Center Contracting Officer

Stirling Technology Assessment Process (STAP)

- <u>Data Collection Phase</u>:
  - NNC15ZMR015L RFI/Sources Sought responses in the form of answers to Stirling Power Technology Questionnaire (Appendix A) due August 5, 2015.
  - Respondents encouraged to answer all questions or relevant subset, clearly marking proprietary information.
  - Government use of RFI information for market research, information and planning purposes. The Government will not pay for the provision of any information received in response to this RFI, nor will it compensate any respondents for the development of any such information.

- <u>Analysis Phase</u>:
  - Assessment team reviews RFI responses.
  - Results shared with RPS Program Manager.
  - Possible follow-on conversations with respondents.

STAP Final Phases

- Conversation Phase:
  - May converse to better understand industry capability and RFI responses.
  - Correspondence, teleconferences, and site visits for facility tours and hardware inspections all possible.
  - May consider procurement and non-procurement actions for further data gathering or to facilitate temporary bailment agreements and hardware loans for Government testing.

- Planning Phase:
  - Document information received for Government planning and opportunities to improve technology development and infusion.
  - Possible recommendations for RPSP funding to test hardware assets at respondent facilities or acquire for further use by the Government.
  - Any contractual actions by NASA, DOE or the Government would be pursued through separate procurement activities.

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RFI Response Format

- <u>RFI Submission Requirements:</u>
  - Responses limited to 20 pages total including figures and references. Use single-spaced, 12-point, Times New Roman font. Requested file formats are: Microsoft Word (.docx) or Portable Document Format (PDF). Where possible, please provided figures in "native file" format to allow for review in greater detail.
  - Send answers to Appendix A as e-mail attachments with subject line: "Stirling Technology RFI Response from [Company Name]".
  - Submit RFI responses via e-mail to <u>Dawn.R.Pottinger@nasa.gov</u> by 11:59 PM Eastern Time on, August 5, 2015.

RFI Response Details and Points of Contact

- RFI Responses shall include:
  - Name of the primary point of contact for the response and business title.
  - Institution or organization affiliation.
  - Postal address, e-mail address, and phone number.
  - Identification of other key individuals who collaborated on the RFI response.
  - Responses to Stirling Power Technology Questionnaire (Appendix A).

- RFI Primary Point of Contact:
  - Dawn R. Pottinger, NASA Glenn Contracting Officer
  - Dawn.R.Pottinger@nasa.gov (216-433-5063)
- RFI Alternate Point of Contact:
  - June F. Zakrajsek, Radioisotope Power Systems Program
  - June.F.Zakrajsek@nasa.gov (216-977-7470)

Government RFI Review Team

- NASA/June Zakrajsek*
- DOE/Dirk Cairns-Gallimore*
- NASA/Jim Withrow*
- UT-Battelle/Lou Qualls*
- NASA/Ed Lewandowski*
- NASA/Dawn Pottinger*
- USRA/Jeff Schreiber*
- NASA/Scott Wilson
- NASA/Lee Mason
- Vantage/Paul Schmitz
- APL/Ken Hibbard
- JPL/Dave Woerner
- Battelle Energy Alliance/Steve Johnson
- DOE/Carl Friesen
- NASA/Jeff Rusick
- NASA/Wayne Wong
- NASA/John Hamley
- NASA/Tom Sutliff
- NASA/Karen Hughes

* Indicates likely travel team member

Stirling Technical Interchange Meeting

TECHNOLOGY MATURATION PROCESS

John A. Hamley
RPS Program Manager

SMD Organization

Associate Administrator (AA) (John Grunsfeld)
Deputy AA (Geoff Yoder)

- Deputy AA for Programs (Greg Robinson)
- Deputy AA for Mgt (Roy Maizel)
- Deputy AA for Research (Marc Allen)

Chief Technologist (M. Seablom)

Planetary Protection Officer (C. Conley)

JWST Program Office
Dir. (E. Smith)*

Embeds/POCs
Chief Engineer (J. Pellicciotti)
Safety & Msn Assurance (P. Panetta)
General Counsel (M. Harrington)
Legislative & Intergvtl Affairs (G. Adler)
Public Affairs (D. Brown)
Intl & Interagency Relations (K. Feldstein)

SCIENCE ENGAGEMENT & PARTNERSHIPS
Dir. (K. Erickson)

RESOURCE MANAGEMENT DIVISION
Dir. (C. Tupper)
Dep. (K. Wolf)

STRATEGIC INTEGRATION & MANAGEMENT DIVISION
Dir. (D. Woods)
Dep. (J. Feeley)

EARTH SCIENCE DIVISION
Dir. (M. Freilich)
Dep. (M. Luce)

JOINT AGENCY SATELLITE DIVISION
Dir. (S. Clarke)
Dep. (J.C. Duh)

HELIOPHYSICS DIVISION
Dir. (J. Newmark-Act)
Dep. (S. Smalley)

PLANETARY SCIENCE DIVISION
Dir. (J. Green)
Dep. (D. Schurr)

ASTROPHYSICS DIVISION
Dir. (P. Hertz)
Dep. (A. Razzaghi)

* Direct report to NASA Associate Administrator

As of April 2015

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SPACE FLIGHT SYSTEMS DIRECTORATE (M)

Director: Bryan K. Smith
Deputy Director: Joel K. Kearns
Associate Director: Scott Graham

PROGRAM/PROJECT INTEGRATION OFFICE (MB)

Chief: Michael J. Zernic

RADIOISOTOPE POWER SYSTEMS PROGRAM OFFICE (MR)

Chief: John A. Hamley

Space Science Project Office (MA)

Chief: Ann P. Over

European Service Module Integration Office (MG)

Acting Chief: Joel K. Kearns

Space Operations Project Office (MS)

Chief: Thomas H. St. Onge

Space Communications & Spectrum Management Office (MSC)

Chief: Elias T. Naffah

ISS and Human Health Office (MSI)

Chief: Robert R. Corban

Space Technology Project Office (MT)

Chief: Trudy F. Kortes

Exploration Systems Project Office (MX)

Chief: Dr. Timothy E. Tyburski

Program Functions With DOE Content

- **RPS**
  - **PRODUCTION OPERATIONS***
    - Operations and Analysis
    - Pu-238 Supply Project
    - Un-fueled RPS Production
  - **MARS ROVER 2020 MISSION SUPPORT***
  - **FUTURE SYSTEMS DEVELOPMENT***
  - **RPS PROGRAM**
    - Education and Public Outreach
    - Program Control
    - Thermoelectric Technology Development
    - Program Planning and Assessment
    - Stirling Cycle Technology Development
    - MMLAE

* NASA-funded DOE activities with unique Inter-Agency Agreement

Radioisotope Power Systems Program (RPSP)

Level II

PROGRAM MANAGER
John Hamley, Manager (GRC)
Tom Sutliff, Deputy (GRC)
Olga Lozano, Adm. Assistant (SGT)

CHIEF ENGINEER
Chris Steffen (GRC)

CHIEF SAFETY OFFICER
Jeff Rusick, Lead (GRC)

PROGRAM CONTROL
Pete McCallum, Manager (GRC)

PROGRAM PLANNING AND ASSESSMENT
June Zakrajsek, Manager (GRC)

DOE INSIGHT
Carl Sandifer (GRC)

EDUCATION AND PUBLIC OUTREACH
Rachel Zimmerman Brachman, Lead (JPL)

MMLAE
Mark Phillips, Manager (JPL)
Paul VanDamme, Deputy (JPL)

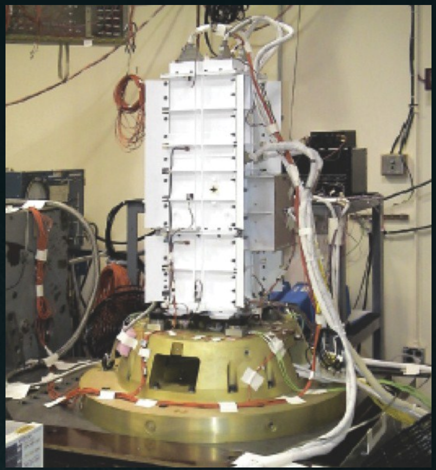
Level III

STIRLING CYCLE TECHNOLOGY DEVELOPMENT
James Withrow, Manager (GRC)

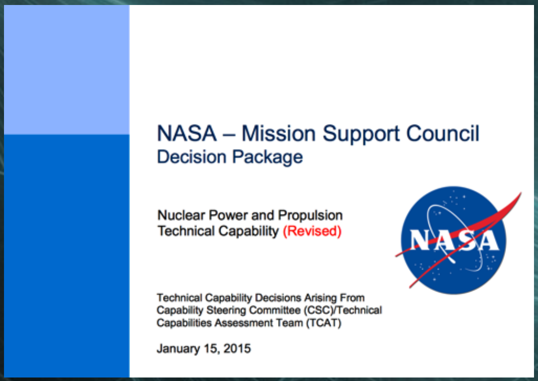
THERMOELECTRIC TECHNOLOGY DEVELOPMENT
Jean-Pierre Fleurial (JPL)

Stirling to Flight (S2F) RFI and Technology Maturation Plans

- Advance Stirling Radioisotope Generator (ASRG) flight project cancelled in early 2014 (pictured to the right)
- Assets redistributed
  - Engineering unit assembled and tested at GRC (pictured, lower right)
- NASA's Technical Capabilities Assessment Team (TCAT) and Agency Program Management Council (APMC) decisions reaffirmed the need for Stirling technology


ASRG undergoing vibration testing at Lockheed Martin


EU2 on extended life testing


NASA – Mission Support Council
Decision Package

Nuclear Power and Propulsion
Technical Capability (Revised)

Technical Capability Decisions Arising From Capability Steering Committee (CSC)/Technical Capabilities Assessment Team (TCAT)

January 15, 2015

TCAT Decision Package

Stirling to Flight (S2F) RFI and Technology Maturation Plans

- RFI released June 3, 2015 seeking sources for Stirling converters and manufacturing
- Stirling Technical Interchange Meeting (TIM) at OAI June 29, 2015
- Responses to RFI Appendix A due no later than 11:59p.m. Eastern Time, on August 5, 2015
- RFI Content
  - Discover Stirling device availability for integration into a 100-500 W_e generator (system)
    - Looking for designs and hardware availability and ability
    - Looking for derivative/scalability potential
    - Looking for IP and potential licensing
  - Discover precision flight hardware manufacturing ability of licensed production of potential convertors for non-commercial, government-only use
  - Discover partnership approaches

Stirling to Flight (S2F) RFI and Technology Maturation Plans

- Technology maturation process planned to mature technology and prepare for flight system development
  - Based on ASRG lessons learned
  - New knowledge from recent operations
  - Requirements development in progress with heavy flight center participation
- Goal is for flight system launch in 2028

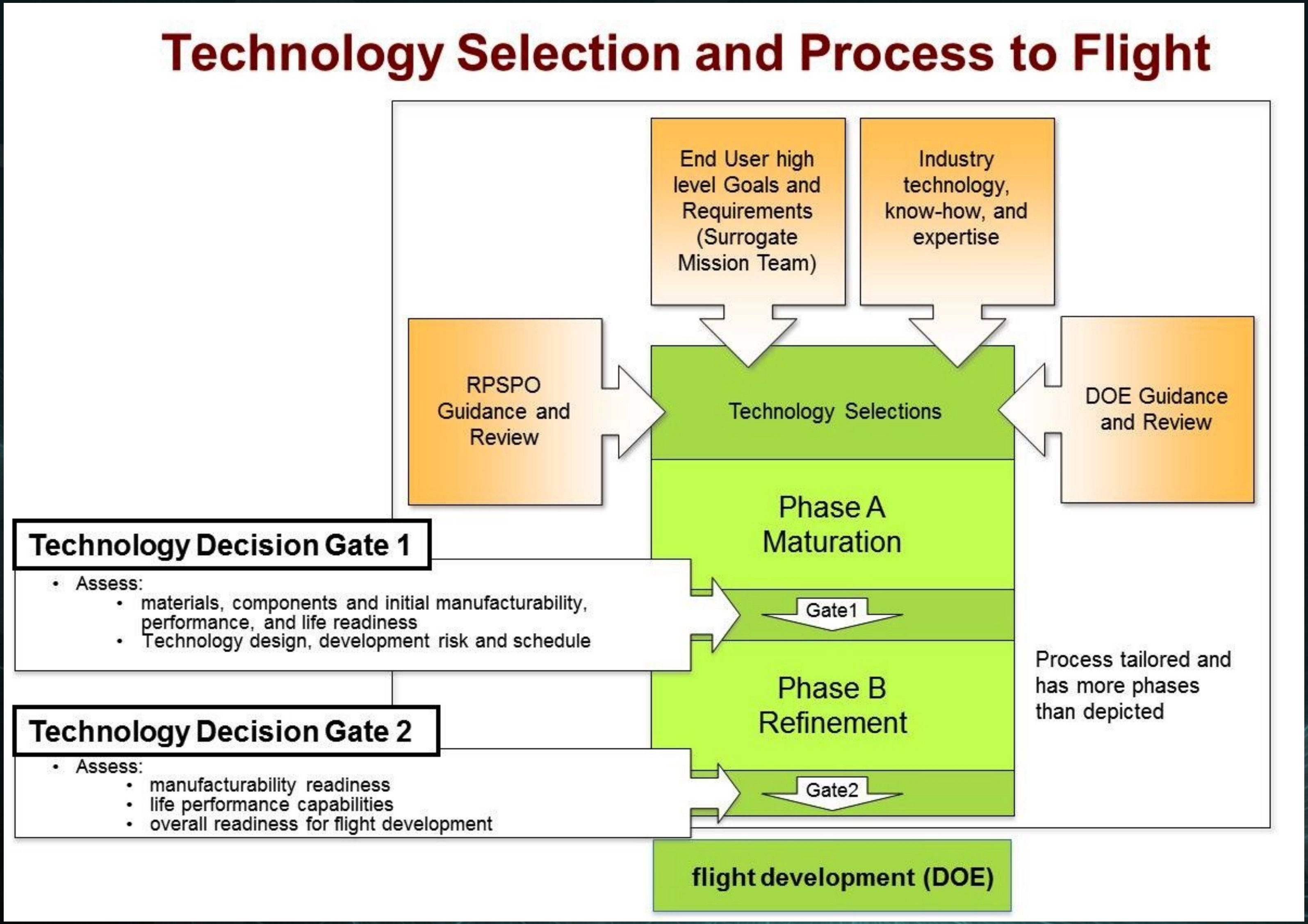
What Are We Looking For?

- Robust, reliable, available system or components that would have simple operation and long life for deep-space missions lasting 10 years or more
- Self-sustaining capability
  - Maintenance of capability without continuous demand from NASA
- Minimal risk and development challenges to reaching TRL of 6
- Understanding of requirements for eventual transition to flight
- Potential development of qualification unit and flight system

What Are We Looking For?

- System Characteristics
  - Reliability/fault tolerance – See RFI for complete definition
  - Robust (margins) – See RFI for compete definition
  - Spacecraft applicability / simplicity
    - Requirements for:
      - Power interface i.e. converter load shedding
      - Commands / Data needed to operate/monitor converter
      - ConOps in flight
      - Ease / simplicity of operation

Technology Maturation Process



Stirling Timeline

- Preparation & Discovery Phase – March 2015 to March 2016
  - RFI
  - Acquisition Strategy
  - Draft functional requirements and technology requirements
- Technology and Smart Buyer Phase – March 2016 to October 2017*
  - Final Mission based SRG Concept of Operations
  - Final functional requirements and technology requirements
  - Assessment of technology readiness for system development
- System Maturation and Development Phase – 2018 to 2023*
- Flight HW Development Phase – 2024 to 2028*

* Tentative
DOE Led Phase

Summary of Information Requested

- Availability or potential availability of Stirling based technology options that could be utilized in a 100-500 W_e power system
- Understanding of current device(s) and state of development
- Device operation. Configuration, mass, performance, operational temperature range, and fault tolerance. Modifications needed to produce power at required level.
- Number of applicable units produced, demonstrated life and reliability, risks to long-term, unattended operation
- Scalability, if required. Projected performance correlated with heat source degradation.
- Experience with production of space-flight or other nuclear hardware

Summary of Information Requested

- What company assets/expertise will be utilized for this activity
- What partnerships; i.e. other industry, NASA, other will be used for the technology development, hardware production, and test
- How will this capability be sustained during periods of non-use by NASA
- Other

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Request for Information

RADIOISOTOPE POWER SYSTEMS PROGRAM

GRC Virtual Facility Tour

Lee Mason
Thermal Energy Conversion Branch Chief

GRC RPS Facilities Overview

Dedicated
- Stirling Research Lab (SRL)
- Vacuum Facility #67
- Radioisotope System Integration Lab (RSIL)
- High Temperature Magnet Aging Lab
- Linear Alternator Test Rig
- Multi-Layer Insulation (MLI) Test Rig

Shared (with STMD)
- High Power Stirling Lab
- Heat Pipe Research Lab
- Vacuum Facility #17

University Support
- Case Western Reserve University, Centrifuge Lab
- University of Dayton Research Institute, Materials Lab
- University of Akron, Gigacycle Spring Testing

Scheduled
- Structural Dynamics Lab (SDL)
- Electro Magnetic Interference (EMI) Lab
- Non Destructive Evaluation (NDE)
  - High Temperature Helium Leak Test
  - Microfocused Computed Tomography
- High Temperature Creep Lab
- Mechanical Testing Lab
- Organic Materials Lab
- Vacuum Facility #6

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GRC Stirling Research Lab

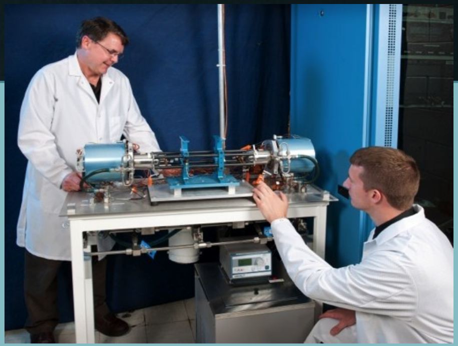
- Established in 1999 to support radioisotope Stirling technology development & transition to flight
- Capabilities include:
  - 14 ambient + 1 thermal-vac test stations; up to 2 convertors each
  - 24/7 extended operation testing with automated fault notification
  - Nuclear heat source simulation with high temperature resistance heaters
  - Cold-end thermal management using water-glycol circulators
  - Commercial and custom convertor controller electronics
  - LabVIEW-based data acquisition; low (2 sec) and high (4-7 khz) speed data collection with data hub
  - Machine shop, gas charging, part inspection, metrology, specialized electronics/circuit boards

SRL has been used to test over 50 different Stirling convertor devices

GRC Stirling Research Lab

- Test stands and data systems permit 24/7 unattended operation allowing long duration tests to demonstrate life and reliability
- Wide range of convertors tested including: Infinia Technology Demonstration Convertors (TDC), Sunpower Advanced Stirling Convertors (ASC), Thermoacoustic, Multi-cylinder, Multi-kilowatt, etc.

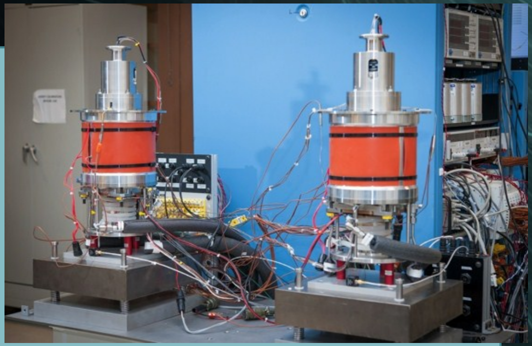
TDC



ASC-0

Conv.	Units	Hours*
TDC	8	372,000
Pre-ASC	10	4,000
ASC-0,1,L	9	137,000
ASC-E,E2	12	203,000
ASC-E3	7	44,000
Total	46	760,000

Over 87 Years* of Cumulative Test Hours



ASC-3

ASC-2

* As of June 2015

RPS System Integration Lab (RSIL)

- Allows electrical verification of RPS in spacecraft context
- Current implementation includes:
  - Breadboard power distribution and control unit
  - Prototype battery and charge/discharge unit
  - Lab-fidelity command and data handling system
  - Array of typical spacecraft power load simulators
- RSIL will be used to evaluate power quality, electrical faults, and electrical load interactions associated with SRG-based power systems

RPS–Related GRC Vacuum Facilities

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Vacuum Facility #67


Vacuum Facility #6


Vacuum Facility #17

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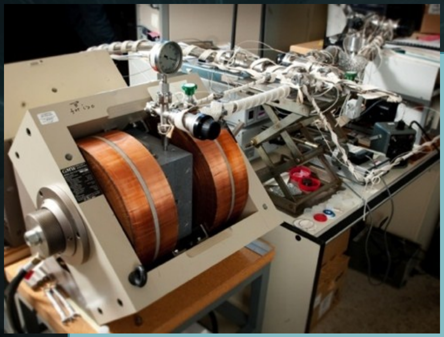
Other Key Labs & Test Rigs

Mechanical Testing Lab

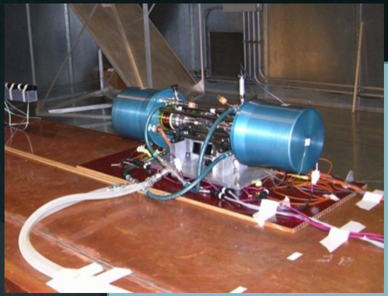
Stirling Feed-through Test Rig

Linear Alternator Test Rig

MLI Test Rig



Magnet Aging Rig

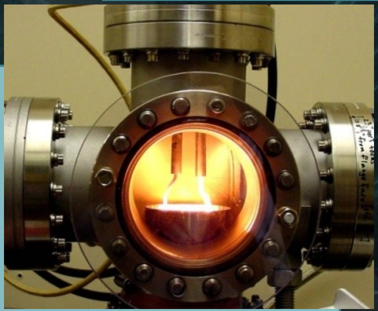


EMI Lab

High Power Stirling Lab

High Temperature Creep Frames

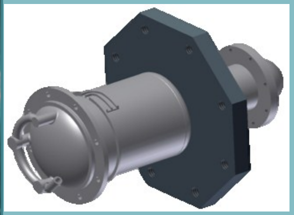
Heat Pipe Research Lab

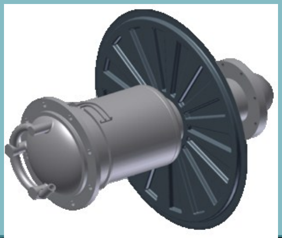


High Temp Helium Leak Test Rig

Microgravity Heat Pipe Testing

- Joint activity between RPS Program, STMD Game Changing Development Program, and STMD Flight Opportunities Program
- Five Zero-G Parabolic Flight Campaigns:
  - 2011-12 Thermosyphon Array with Controlled Operation (TACO) – evaporator flooding limits (2 flights)
  - 2013-14 Heat Pipe Limits Experiment – SRG radial core heat spreader and Kilopower heat pipe (3 flights)
- 2015 Peregrine Sounding Rocket Flight Experiment – SRG radial core heat spreader





Stirling Technical Interchange Meeting

GRC VIRTUAL TOUR VIDEO

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Stirling Technical Interchange Meeting

LUNCH

Stirling Technical Interchange Meeting

PARTICIPANT OVERVIEWS

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STIRLING TECHNICAL INTERCHANGE MEETING

CLOSING REMARKS

JOHN A. HAMLEY

RPS PROGRAM MANAGER

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STIRLING TECHNICAL INTERCHANGE MEETING

ONE-ON-ONE INFORMATION DIALOGUES

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Stirling Technical Interchange Meeting

BREAK

STIRLING TECHNICAL INTERCHANGE MEETING

ONE-ON-ONE INFORMATION DIALOGUES

Glenn Research Center
Jet Propulsion Laboratory
Applied Physics Laboratory

Idaho National Laboratory
Los Alamos National Laboratory
Oakridge National Laboratory
Sandia National Laboratory